MAGNETIC POLES AND ENERGETIC PHOTON SHOWERS IN COSMIC RAYS*

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Various anomalous high-energy pure photon showers seen in cosmic-ray emulsions are interpreted in terms of properties expected for the production of bound pole-antipole pairs. It is argued that such bound pairs are the most likely state for created monopoles.

We attempt to give a plausible description of a collision process in which a magnetic pole-antipole pair would be produced. Because of the very large coupling, $g^2/\hbar c \approx 137$, of the pole to the electromagnetic field,[1,2] such a process is expected to have the following particular features.

(1) The mass M of the pole must be very large, satisfying $M \gtrsim \frac{1}{2}(g^2/\hbar c)m_\pi \approx 10$ BeV.

(2) To escape each other's strong long-range attraction, the pole's relative velocity must be relativistic for initial separations $\sim 10^{-13}$ cm.

(3) In such cases the energy carried off in a photon shower probably greatly exceeds the pole rest energy, so very large energies must be supplied for production of a free unbound pair.

(4) Because of the energy taken away by such radiation in most above-threshold ($>2Mc^2$) cosmic-ray collisions, if a pair is produced, it may usually remain bound by its strong, long-range attraction. It would ultimately reannihilate after successive photon emission from descending Bohr orbits with a photon shower as its only remnant.

(5) These expectations suggest a possible scenario for certain remarkable very high-energy photon showers discovered in high-altitude cosmic rays. We discuss these points below:

(i) At sufficiently large distances and low velocities the interaction between a pole-antipole pair is described by the familiar Coulomb-law attraction $V(r) = -g^2/r$, but with a force $\sim 2\times 10^4$ greater than for an electron-positron pair. The lower bound on the pole mass holds because the sum of this negative potential energy plus the rest masses of the pair must be positive at distances sufficiently large that the motion of the massive poles may be described classically. Vacuum polarization corrections can only lower the potential energy at any r. The structure or form factor of the poles, together with the possible exchange of strongly interacting mesons, would qualitatively alter this potential only for $r \lesssim r_0 = \hbar/m_\pi c \sim 10^{-13}$ cm, corresponding to the Compton wavelength of the lightest hadron. Hence, in order for the vacuum to be stable against spontaneous production of pole pairs at separations down to r_0, M must satisfy $2Mc^2 - g^2 m_\pi c/\hbar \gtrsim 0$. Consequently, production of a pole-antipole pair in, say, a proton-nucleon collision requires a proton laboratory energy exceeding 200 GeV.

(ii) Even if all subsequent radiation is ignored, the pole kinetic energy at r_0 must exceed $g^2/r_0 \sim 20$ GeV, to escape the strong mutual attraction, so the poles' relative velocity v_0 at r_0 must exceed $(v_0/c)^2 \gtrsim 4(g^2/\hbar c)(m_\pi/M)$. A similar restriction follows from the condition that radiation, caused by deacceleration in the magnetic Coulomb field beyond r_0, not slow the pole to below escape velocity. Therefore, unless the pole mass very greatly exceeds the lower limit $(g^2/2\hbar c)m_\pi$, the pole and antipole will only escape each other for relativistic relative velocity at $r = r_0$. But, as discussed next, because the poles are so enormously strongly coupled to photons, they may only rarely acquire relativistic energies in the creation process.

(iii) The creation and acceleration of a pair of magnetic poles will always be accompanied by a large emission of soft photons. The probability that the monopole pair is suddenly emitted with velocity $v \sim c$ without an energy loss exceeding ΔE to any dipole photon is approximately $\exp[-(8g^2/3\pi\hbar c)\ln(mc^2/\Delta E)]$, which holds when the energy given to any one photon is less than the inverse acceleration time $\tau \sim r_0/c$. For magnetic monopole pair emission at an extreme relativistic relative velocity, the energy emitted into "soft" photons would be $(g^2 m_\pi/M)[1-(v/c)^2]^{-2}Mc^2$. Thus the kinetic energy with which the fast monopole leaves the region $r<r_0$ should be much smaller than that of the accompanying soft protons. [Subsequent deceleration by the magnetic Coulomb attraction between monopoles would result in a further loss to radiated photons $(g^2 m_\pi/M)^3 Mc^2$. This division into emission regions is adequate only for those "soft" photons whose frequency is not small compared with τ^{-1}.]

Such emission of soft photons is an essentially classical phenomenon. The emission of hard photons, of course, depends upon the dynamical details of monopole creation. In the absence of a detailed model we note that in the energy budget suggested by the statistical model, there is an equipartition of energy between the monopoles and many hard photons in thermal equilibrium with them at the very high temperatures $kT \sim Mc^2$ necessary for relativistic emission.

(iv) The above considerations of soft and hard photons suggested that the c.m. energy may have to exceed $2Mc^2$ enormously, in order to create a free pole-antipole pair. Instead of an unbound pair, it is overwhelmingly more likely, in most above-threshold collisions ($E_{\mathrm{c.m.}} > 2Mc^2$), that a bound pair of monopoles be produced in a Keplerian orbit, whose lifetime against subsequent annihilation depends upon the time for further radiation to bring them back within a distance less than r_0. However, for emission into a highly eccentric orbit, which carries the pair out to a maximum relative distance $\sim 10^{-12}$ cm, the duration before returning to the region $r < r_0$ is of the order of 10^{-22} sec and is not qualitatively affected by radiation.

(v) Remarkably, in high-altitude cosmic-ray exposures, a number of very peculiar energetic narrow pure photon showers have been photographed which have not been interpreted as conventional showers.[3-5] They are characterized by a very energetic narrow cone of some tens of γ rays without incident charged particles. The radial spread of photons in the plate suggests a c.m. velocity corresponding to $\gamma \gtrsim 10^3$. When transformed back to the c.m. system many of the photon energies are orders of magnitude too low to have π^0 decays as their source. (Furthermore, the greater energy of some of the downstream γ rays is contrary to the behavior in usual photon showers initiated by a very few photons.) In addition to the multiplicity another significant and peculiar characteristic is, in some cases, a large gap comparable to a radiation length before any γ-ray conversion is seen.[4] If not a remarkable statistical fluctuation this can be understood only if the narrow photon cone were produced in the emulsion itself.[6] The expected properties of bound pole-antipole suggest a possible scenario:

The production of the bound pole-antipole results in a photon shower whose multiplicity, though depending on dynamical details, is roughly of order $g^2/\hbar c \sim 10^2$. The number of relatively soft photons depends critically on the pair separation and duration in the bound system. For single radial excursion to 2×10^{-12} cm and subsequent reannihilation, the associated soft photon emission cuts off sharply below 1 MeV and goes roughly like the usual $g^2 d\omega/\omega$ above this. The existence in some emulsions of a gap of almost a radiation length before any γ-ray conversion suggests that it is a high-energy photon which produced the bound pole-antipole pair within the plate.[7] This is not implausible since the photon is more strongly coupled to this system than to any known hadron. The mechanism would be analogous to that for electron-positron production.[8] In order that the momentum transfer to the participating nucleus be small compared with the nuclear radius (i.e., nuclear charge form factor ~1), the incident γ-ray energy E_γ must satisfy $E_\gamma \gtrsim 4A^{1/3}M^2c^2/m_\pi$. Then for a bound pole pair of approximate mass $\lesssim 2M$, the center of mass of the photon shower has $\gamma \gtrsim E_\gamma/2Mc^2 \gtrsim 2A^{1/3}M/m_\pi \gtrsim A^{1/3}(g^2/\hbar c) \sim 10^3$ for a silver target nucleus. This γ is consistent with that deduced from observations. Incident γ rays of energy 10^{13} eV necessary for the production of such bound pairs do exist as decay products of π^0 mesons produced at comparable energies at high altitudes.

At 10^5 ft (corresponding to $\frac{1}{3}$ of a mean free path for collision of a primary cosmic-ray proton), the flux of π^0 secondaries of energy exceeding 10^{13} eV is expected to be about 10^{-8} cm^{-2} sr^{-1} sec^{-1} in the zenith direction. For an emulsion stack (150-cm^2 area and about 1-cm thickness) the number of π^0-decay γ rays of energy greater than 10^{13} eV which traverse the stack is then of order unity per stack per day. If the cross section for producing bound pole pairs by such energetic γ rays begins to approach that for direct e^--e^+ production,[9] then the expected number of "peculiar" high-energy pure-photon showers produced in emulsions is comparable with the number which have been observed.[10]

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[6]The event of Ref. 3 does not possess such a gap.

Dr. Haskin's current view of this event favors the interpretation of it as a rare statistical fluctuation in a conventional photon shower initiated in the very thin aluminum case around the emulsion. We are grateful to him for a conversation about it.

[7]Such a bound pole pair would not cause observable ionization as long as the separation is much smaller than 5×10^{-11} cm. Moreover, unless the pole rest mass greatly exceeds 100 BeV, for $\gamma \sim 10^5$ the distance travelled before annihilation would be less than a micron.

[8]We note that it is characteristic of electron-positron production by γ rays that their relative kinetic energy is usually of order $m_e c^2$. If the pole pairs produced by this same process have a relative kinetic energy Mc^2, then the strong photon emission which accompanies them would be particularly effective in reducing the relative velocity below that needed to escape.

[9]In a perturbation-theory estimate which neglects pole structure, radiation damping, and final-state enhancement, the ratio of pole-pair production cross section to that for e^--e^+ is $(g^2/e^2)^2(m_e/m)^2$, which is indeed of order unity for $M \sim (g^2/\hbar c)m_\pi$. However, there is obviously no reason to consider perturbation theory as a guide since $g^2/\hbar c \gg 1$, and in fact it gives a cross section, near threshold, for pole-antipole production in a two-photon collision which greatly exceeds the unitarity limit.

[10]The energetic photons from annihilation of bound pole pairs would result in anomalous extensive air showers without any appreciable muon or other penetrating component. For reports of such showers see, for example, J. Gawin, J. Hibner, J. Wdowczyk, A. Zawadzke, and R. Maze, in Proceedings of the Ninth International Conference on Cosmic Rays, London, 1965 (The Institute of Physics and The Physical Society, London, 1966), Vol. 2, p. 639.

PHOTOPRODUCTION OF $\pi^-\Delta^{++}(1236)$ FROM HYDROGEN FROM 5 TO 16 GeV*

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The cross section for $\gamma p \rightarrow \pi^-\Delta^{++}(1236)$, measured at 5, 8, 11, and 16 GeV from near-zero momentum transfer to -1 GeV^2 (-2 GeV^2 at 16 GeV), rises from small t to a maximum near $-t = m_\pi^2$, then falls as e^{12t} out to $-t \approx 0.2$ GeV^2, after which it becomes roughly equal in slope and magnitude to the single π^+ photoproduction cross section (e^{3t}). At fixed t, the cross section varies as k^{-2}, where k is the laboratory photon energy. The results do not agree well with the simple vector-dominance model.

The differential cross section for

$$\gamma p \rightarrow \pi^-\Delta^{++}(1236) \tag{1}$$

has been measured at 5, 8, 11, and 16 GeV using the Standard Linear Accelerator Center 20-GeV/c spectrometer system.[1] This work extends previous measurements in the few-GeV region.[2]

The apparatus and method are the same as used by Boyarski et al.,[3] with two modifications. First, in addition to the Čerenkov monitor, a secondary-emission quantameter was used to monitor the beam. Except for laboratory angles $\leq 1°$, these two monitors could be used simultaneously and provided a cross check of the monitor stability; in general, this stability was found to be about $\pm\frac{1}{2}\%$. These monitors were calibrated against two precision calorimeters which served as absolute standards. The second change was the use of a threshold gas Čerenkov counter to separate the group e, μ, π from K mesons and protons. As before, the pions were then identified by their interaction properties.

To determine the Δ^{++} yield, the 20-GeV/c spectrometer system was used to measure the momentum spectrum of π^- mesons produced in hydrogen by a bremsstrahlung beam. This yield of π^- mesons was determined as a function of missing mass (calculated for $k = E_0$, the bremsstrahlung end-point energy); $\Delta^{++}(1236)$ production should appear as a step in the π^- yield versus missing mass at $M_x^2 = 1.53$ GeV^2, reflecting the step in the photon spectrum near the end point. The width of the rise of the step is mainly determined by the natural width of the Δ with a small contribution from the experimental resolution. Data were normally taken over the range $1.2 \leq M_x^2 \leq 2.5$ GeV^2.

For process (1) the shape of the Δ was assumed to be given by a Jackson relativistic Breit-Wigner form[4]

$$R(m^2) = \frac{1.13}{\pi} \frac{m_0\Gamma(m)}{(m^2 - m_0^2)^2 + m_0^2\Gamma^2(m)} \tag{2a}$$